Tobiko: A Contact Array for Self-Configuring, Surface-Powered Sensors

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ABSTRACT
This paper describes a contact array that outputs the maximum and minimum voltages at its contacts. The goal is to extract power for a detachable touch sensor, display, or other human-computer interaction (HCI) device that is attached to a surface by a user, and that does not have its own power source. Experimental results are shown for an array that has positive and negative outputs and a pass-through at each contact position. It solves the startup problem for a randomly-placed batteryless sensor patch or sticker, which can scan its ports to discover neighboring devices only after it obtains power. Applications include user-configurable electronic textile circuits, and new methods for prototyping and repairing large-area flexible circuits. This note describes construction of a 7x7 array, provides design rules, and examines the signal quality on two kinds of electronic surfaces.

Author Keywords
Contact array; self-configuring; e-textiles; wearables

ACM Classification Keywords
B.4.3. Interconnections (Subsystems): Interfaces

INTRODUCTION
Self-configuring circuits will drive the development of HCI applications that use wired sensors and actuators. Demand for local control or local information should determine sensor and actuator locations, rather than the availability of a power plug or signal wire. The need is strongest in HCI applications where device locations aren't planned ahead of time, for example a smart home controlled by user-placed wall stickers [1], or a biochemical sensor monitoring a wound for signs of infection [2], attached to a patient-worn electronic textile (e-textile) garment.

This note describes a physical interface that can extract power for an electronic device in contact with a larger underlying circuit such as an e-textile or wallpaper, without needing any alignment.

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MOTIVATION
In most current e-textiles, the communications interface and power electronics—including battery packs and wireless modules—are still detached before washing, while embedded fiber sensors [3], conductive traces including antennas [4], and small integrated circuits [5,6] increasingly stay with the textile. Connectors between electronics and e-textiles are becoming more robust, flexible, and elegant [7] but once a connector is embedded, the circuit is fixed, making it difficult for the end user to add new sensors and actuators to the e-textile. Modular circuits with replaceable tiles are one way to add user configurability to a large-area circuit [8,9]. Connectors with large numbers of contacts to far-off areas are another approach to create room for expansion. Solder bumps for a multi-pin pocket connector address the problem of a detachable e-textile connection for a large-N pin array, as long as the device can be aligned to within 5mm [10].

Outside the domain of e-textiles, researchers have sought to charge or communicate with devices that make direct electrical contact without alignment. These efforts include Open Dots [11], Networked Surfaces [12,13,14], and the Smart Table [15]. The Smart Table aims to locate devices placed on an active electrode grid. Its methods might complement the work here, which uses a passive electrode array. Networked Surfaces consist of pads and a circular array of contacts on a sliding device, while Open Dots is an array of four contacts for device charging on an electrode grid. These approaches are robust when used on printed circuit boards (PCBs) with fixed geometry. However, as electronic connectors evolve toward stretchable materials, the contact arrays will not remain dimensionally stable. There can be no expectation to attach a multipin contact in registration from one location to the next. Another problem is that in both e-textiles and stretchable electronics on thin polymer films [16], conventional PCB fabrication methods cannot generally be used because of the low temperature tolerance of the substrates. Anisotropic materials such as zebra connectors [17] and z-axis conductive tape [18], and emerging materials like liquid metal alloys [19] address the solderability problem, but not the problem of alignment between two deformable circuits, or between a conventional rigid circuit and the surface of an e-textile that may shear or slip during use. New materials and methods are needed for creating reconfigurable and repairable HCI systems based on soft, moving materials.

APPLICATION CASES

Envisioned HCI applications of smart contact arrays are:

- Electrical connections for user-positioned sensors on wallpaper, tablecloths or other soft HCI surfaces
- Repair "materials" enabling a non-expert user to identify and reconnect broken traces on a large-area HCI circuit
- Connectors for human activity sensors on materials that can move and distort, especially clothing.

In the last case, the array may collect analog signals from passive sensor elements built into the surface, like embroidered electrodes for measuring muscle signals [20], or resistive strain sensors made from knit conductive threads. Lightweight, repositionable sensors that can draw power from a shared battery pack will help customize these garments. When tracking muscle activation sequences with sensors, a one-size-fits-all approach fails because there are anatomical landmarks that are well defined [21], but that differ from person to person. The need for spatial customization is one of the problems limiting the adoption of smart athletic garments [22]. This note demonstrates rigid contact arrays, but body-conforming arrays could be achieved with flexible and stretchable substrates.

OPERATING PRINCIPLE

In the "Tobiko" array demonstrated here, the circuit obtains power for itself by tapping into a surface having positive and negative voltage traces at unknown locations with respect to the contacts. Although the circuit is placed randomly on the power electrodes, and the power electrodes are allowed to have defects and distortions, their geometry is important and will be discussed.

Each contact pin is connected to two diodes and a pass-through as illustrated in Figure 1. The diodes produce a rectified power signal and maintain isolation between contacts that touch positive and negative traces on the underlying circuit, while the pass-throughs transmit any communication signals originating from the surface. The circuit at each contact is a standard two-sided "diode clipper" circuit, except that the clipper limits are provided by the surrounding contacts instead of by power supplies.

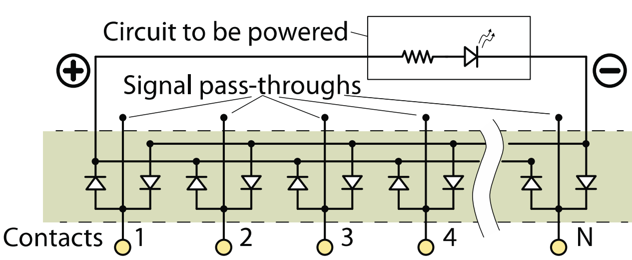

Figure 1. Schematic of array of power collection diodes and signal pass-throughs.

To prevent shorting, the contact pins must be narrower than the smallest gap on the power circuit. With random alignment, many of the pins will not contact a circuit trace; for example pin 3 in Figure 2. The array must span at least one positive and one negative contact (and preferably more because of defects) to ensure that the on-board electronics receive power.

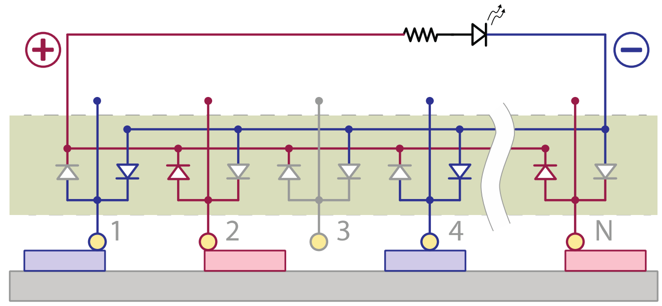

Figure 2. Contact array collecting power from an inter-digitated electrode surface. Grayed-out diodes do not conduct.

CIRCUIT ASSEMBLY

The Tobiko circuit was realized as a sandwich between two PCBs. The contacts were made by soldering 1/16 inch (1.6 mm) diameter brass spheres to 1mm diameter via using solder paste. Between the two boards, diodes (STMicroelectronics TMMBAT48FILM) were soldered on end, two per contact point as shown in Figure 1. The pass-throughs were made from 0 ohm resistors (Vishay). All components were in mini-MELF format. The assembly was run through a reflow oven to finish bonding the spheres and components to the pads on both sides of the board. The top side of the board had a emitting diode (LED) and a pair of contacts for sampling the rectified voltage, and a via to provide a test point for each pass-through signal. The final contact spacing was 4 mm. Figure 3 shows the assembly process and a view of the finished board.

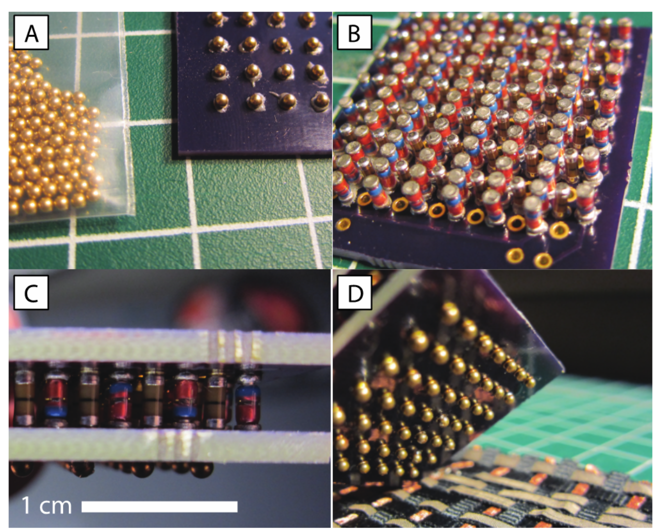

Figure 3. A: contacts, B: diode and pass-through assembly, C: sandwich showing components between boards, and D: underside of array before contact with a soft circuit.

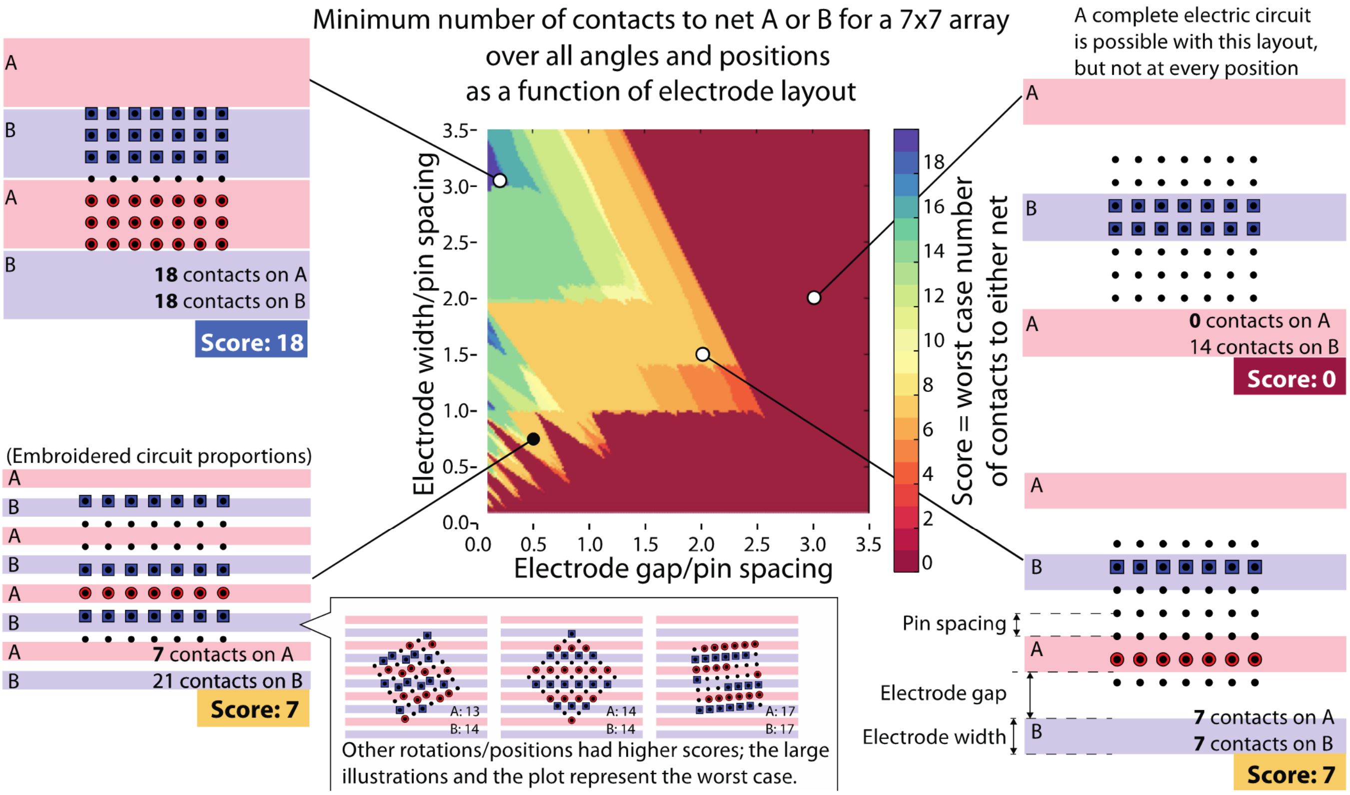

Figure 4. Center image: Relationship between array pitch and optimal design for an interdigitated power surface. The plot shows the worst-case number of contact pins to the least-contacted net (whether the A or B net) over all positions and rotations of a 7x7 array. Outer images: illustrations of the electrode array and interdigitated electrodes at different positions on the center plot. Black dots are pins that make contact with neither the A nor B electrode.

PREDICTING THE CONTACT QUALITY

A Square Grid as the Contact Array

A 7x7 square grid (49 contact points) was used as a test case for both simulations and experiments.

Interdigitated Electrode Arrays as Power Sources

The underlying circuit can have any arrangement that, on average, will put some of the contacts on a positive and others on a negative electrode. Interdigitated positive and negative electrode arrays can be described using only two parameters: the electrode width and the electrode gap. An interdigitated electrode surface was therefore used as a test case to simulate the number of contacts over a continuous range of electrode widths and gaps, in units of contact pin spacing.

Calculating the Worst Case Contact Number

The electrodes and contact array were modeled in Python [23] for angles between 0 and 90 degrees, and center position ranging from the center of one electrode, to the center of the neighboring gap. Because of symmetry, this range covers all possible array positions with respect to the electrode pattern. The code translated and rotated the 7x7 array over the interdigitated electrode pattern, keeping track of the lowest number of pins touching the positive and the negative net (whichever was least) during all the positions and orientations. In the interdigitated pattern, a net consists of every other electrode, denoted in Figure 4 as A and B. The "scores" in this figure are the least number of pins contacting either of the two nets at all positions. If at any position, a configuration was found that made no contact to either one of the nets, that electrode width/gap combination received a score of 0. The central image shows a complex boundary to the "safe" zone of electrode configurations that provide more than one or two contacts at the worst case position. However, there is a solid zone of higher numbers (more reliable contact) as the electrode gap is made smaller and as the electrodes are made wider than one pin-spacing unit. The black dot marks the configuration used in experiments on an embroidered interdigitated circuit.

Interdigitated electrode patterns at the lower left corner of the contiguous safe zone (for example, a relative width of 1 and electrode gap of 0.1) should be able to *stretch* with respect to the pin spacing and still power the onboard circuit at any orientation, as long as the growing widths and gaps do not cross into the red zone. The dimensions of the array and contacts are limited by the materials as listed in Table 1 for the demonstration device, and for a potentially smaller system adaptable to curved surfaces, a PCB surface with a ball grid array (BGA) device.

System	Maximum pin width	Minimum electrode gap	Minimum pin spacing
E-textile/ PCB	1 mm spring pin diameter	~1.5 mm	~2mm
PCB/BGA	0.3 mm	~0.5 mm	~0.6 mm

Table 1. Limits on device dimensions in two materials systems

EXPERIMENTS

Power Collection from Two Kinds of Electronic Surfaces

From an interdigitated array

An embroidered conductive thread array (Figure 5A) with gap of 2 mm (0.5 pin spacing) and spacing of 3 mm (0.75 pin spacing) was supplied with 0 and 5V. The thread was silver-plated nylon. Tests were carried out by lifting and placing the device at a new position. The red LED indicated a successful circuit with no open-circuit errors in 100 different placements with the array horizontal (as in the lower left illustration of Figure 4) and 5 errors in 100 placements at 45 degrees.

From an electronic textile circuit

An e-textile circuit made from woven strips of conductive fabric (Figure 5B) was driven with 5V and contacted to the 7x7 array. The purpose was to extract power from a soft circuit not designed specifically for power sourcing. The LED was illuminated when the Tobiko board rested on the two active traces.

Effect on signals

A function generator, outputting a sine wave, was connected to the pass-through resistor on a pin that was not contacting 5V or a grounded electrode. This setup represented a pin touching a signal trace. The output was compared to the original sine wave signal on an oscilloscope.

DISCUSSION

The interdigitated electrodes performed nearly without errors as expected based on their location on Figure 4 (black dot). At 45 degrees, the few errors were connected to the underlying electrodes having a slight saddle shape, leading to non-contact of the diagonal rows at some positions. This problem could be remedied by using spring contacts or by making the array from conformal materials.

During experiments, the maximum voltage difference available at the Tobiko terminals was 1.44 V less than the maximum power difference on the soft circuit. This voltage drop originated from the two diodes in the current path of Figure 2 (~0.7 V per diode). It could be reduced by using transistors instead of diodes, as is common in battery reversal protection circuits. Sine-wave signals exceeding the 0-5V range of the interdigitated electrodes were distorted as the function generator became the current source for the onboard LED. For example, current was able to flow from the function generator to the LED at sub -0.7V parts of the symmetric sine wave, reducing its negative-going voltage by 20%. If signals outside the expected power range must be used, distortion could be mitigated by active switching. A changing voltage detected at a microcontroller pin while other pins remained at 0 or 5V would indicate a signal (rather than sliding of the whole array). The signal pin could then be disconnected from the power-collection circuit using transistors. When used in a battery-free contact array, this active approach would depend upon a passive contact array to initially power up the onboard electronics.

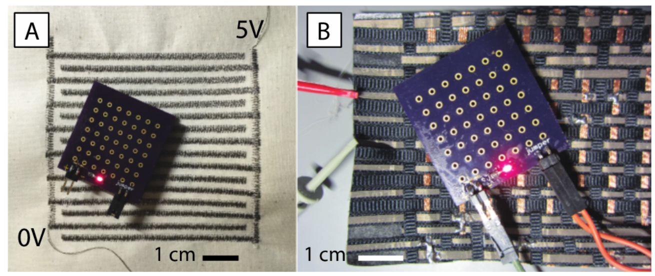

Figure 5. A: Power collection from embroidered interdigitated electrodes with 2mm gap and 3mm width. B: Power collection from an operating e-textile circuit.

CONCLUSIONS

Closely-spaced power electrodes like those in the top left of Figure 4 give the greatest assurance that the circuit will find power. However, a larger electrode gap creates space in the layout for other electrodes that carry signals instead of power. Therefore, layouts like the one in the lower right of Figure 4 are preferable for self-configuring applications that need to communicate over the surface, even though fewer contacts are made to the power source. A larger array is another path to more complex circuits. Even the worst case at the top right of Figure 2, with its large electrode gaps, would always touch both power nets if it were a 10x10 instead of 7x7 array. A larger device area has drawbacks for miniaturization, but it pushes the viable area of the plot in Figure 4 out to larger electrode gaps which would make room for sensor communication lines.

In this report, the diodes were discrete, putting a lower limit on the pin separation. Smaller surface mount packages and automated assembly equipment could reduce the pin spacing below 4mm, but further miniaturization and softer connectors would come from integrating the semiconductor materials directly into flexible substrates for a conformal contact array. With increased pin density, the probe sheet could become a continuous film capable of running user-configurable HCI applications on top of large-area circuits.

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